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POLAR CONVECTION MONITORING DETERMINATION OF THE IMF BZ AND BY ORIENTATIONS FROM DIGISONDE DRIFT VELOCITIES

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13. ABSTRACT *(Maximum 200 words)*

Statistics for one year of Digisonde drift velocities recorded at Qaanaaq (Greenland) are used to derive a method to determine the sign of the interplanetary magnetic field Bz and By components. The Digisonde velocities show characteristics expected from the theoretical understanding of the two-cell and four-cell convection pattern which can exist at high latitudes when the IMF Bz < 0 and Bz > 0 respectively. The derived method is able to determine correctly the orientation of the IMF in 60 to 70% of the cases tested. Considering that the method uses only 15 minute drift velocities recorded at one station (Qaanaaq), the method shows enormous potential for accurately determining the orientation of the IMF components, and assisting in the mapping of the convection pattern when more data from Digisonde stations are introduced in the analysis.

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1. INTRODUCTION

In recent years, a great deal of study has been devoted to the understanding of the interaction of the Interplanetary Magnetic Field (IMF) and the Earth's ionosphere. In trying to understand the electrodynamic system set up by the coupling of particles, fields and electric currents, several empirical and mathematical models have been developed to map out the convection patterns setup in the high latitude regions [Sojka et al 1986; Heppner and Maynard 1987; Hairston and Heelis, 1990]. In order to specify the convection pattern precisely these models require, as a minimum, inputs for the orientation of the IMF (sign of Bz and By components), and the position of the dayside cusp region and nighttime Harang discontinuity region. The essential advantage of these models lies in their ability to specify the real time convection pattern. In order to do this, real time data gathering of the required IMF and high latitude ionospheric responses is needed.

A network of ground-based observation stations (i.e. as is possible from the deployment of digital ionosondes), are capable of measuring and tracking rapid changes in the orientation of the IMF Bz and By components [Reinisch et al., 1987; Cannon et al. 1991] and the ionospheric behavior to these changes. Digital ionosondes are low maintenance, continuously operating instruments that simultaneously measure the electron densities and plasma velocities; the data can provide real time inputs for the specification of the convection models.

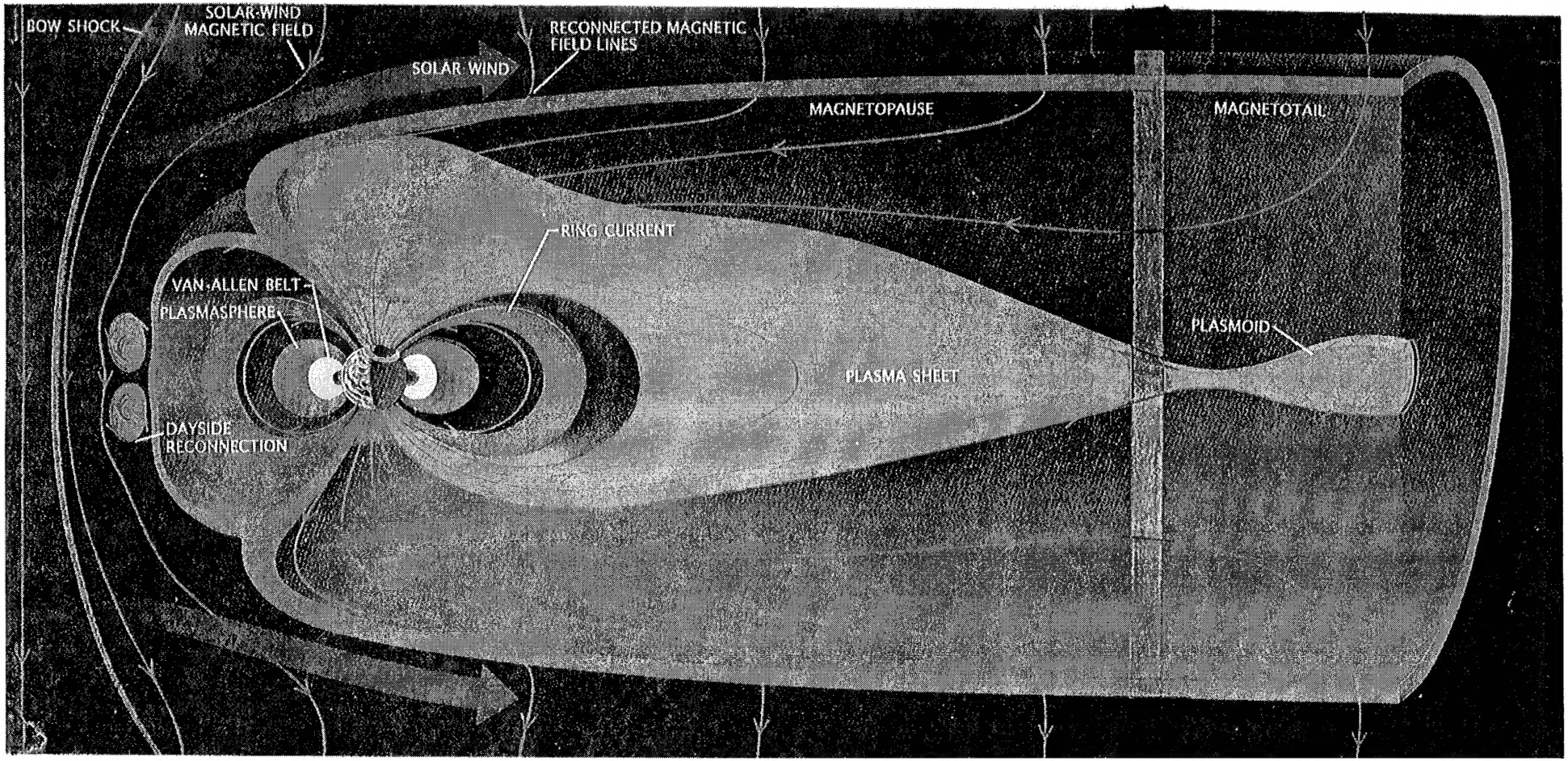
This report discusses the use of Digisonde drift velocities to determine the orientation of the IMF Bz and By components. Section 2 discusses the theory of the interaction of the IMF with the Earth's magnetic field, and the relations between the Bz and By orientations with convection patterns and velocity signatures observed by the Digisonde 256 system. Section 3 incorporates the statistical data base gathered by the Digisonde located at Qaanaaq and introduces criteria that help characterize the Bz and By orientations. Section 4 discusses the results of the analysis technique used to determine the Bz and By orientations and attempts to give an indication as to the reliability of these determinations.

2. INTERACTION OF THE IMF AND THE EARTH'S MAGNETIC FIELD

The interaction of the Earth's magnetic field with the IMF is observed in the magnetospheric-ionospheric system as the development of electro-dynamic processes and the transfer of energy (via merging of field lines). An understanding of the dynamics involved is essential in order to better understand the effects that the Bz and By orientations have on high-latitude convection patterns. To a first order approximation, excluding the effect of the solar wind, the Earth's magnetic field can be considered to be a dipole in which the magnetic field lines loop from the south pole to the north pole. Including the solar wind this tends to confine the Earth's magnetic field to a comet-shaped volume as shown in Figure 1.

Since the charge in the solar wind experiences a force due to the Earth's magnetic field given as F=qVxB, these charges will be deflected around the earth. This has the effect of establishing secondary magnetic fields which cancel the earth's field on the sunward side and increase the value of the magnetic field on the nightside. The result, as observed in Figure 1, is to compress the magnetosphere to about 10Re (where Re = Earth radii) on the dayside, and elongate the magnetosphere to distances as much as 1000Re on the nightside. In addition, the Earth slows down these charges from speeds as much as 400 km/s creating a bow shock (Figure 1).

Due to the "frozen-in" condition, the solar wind carries along with its plasma its own magnetic field. This magnetic field commonly referred to as the interplanetary magnetic field can interact with the Earth's magnetic field in two ways. On the dayside, dependent on the orientation of the Bz component, the solar wind magnetic field can "merge" with the Earth's magnetic field allowing the plasma to enter the Earth's magnetospheric environment, spiral along the magnetic field lines to the poles and be deposited at ionospheric heights. On the nightside, the solar wind may reconnect with the Earth's magnetic field similarly transferring energy. Magnetic field lines extending beyond the magnetosphere are called "open", while field lines extending to the boundary layer of inner magnetosphere are called closed. It is the establishment of electric fields along the opened and closed field lines that drive the convection pattern at high-latitudes.



SOLAR WIND, a diffuse plasma of protons and electrons streaming from the sun, confines the earth's magnetic field in a comet-shaped cavity called the magnetosphere. The wind compresses the magnetosphere on the day side to a distance of about 10 earth radii. On the night side the wind sweeps the earth's magnetic field into an elongated volume known as the magnetotail, which extends for at least 1,000 earth radii. The boundary of the magnetotail is called the magnetopause. The solar wind has a magnetic field (*red*). When it is directed southward, as is shown here, it can "reconnect" efficiently with the earth's field (*blue*). Solar-wind particles flow into the magnetosphere along the reconnected field lines. Magnetic field lines in the north lobe of the magnetotail point toward the earth; those in the south point away. Reconnection of field lines in the magnetotail can pinch off clumps of plasma known as plasmoids, which are ejected from the magnetotail.

Figure 1. Artist view of Earth's magnetic fields and the Solar wind. Taken from Scientific America May 1989, page 58.

Figure 2 shows how the IMF may merge with the Earth's magnetic field dependent on the orientation of Bz. Considering a Geocentric Solar Ecliptic coordinate system, for Bz southward (Bz<0, Figure 2b), merging occurs at high latitudes [Crooker 1986]. For Bz northward (Bz>0, Figure 2a) merging moves poleward of the dayside cusp [Russell, 1972]. Where the field lines merge is crucial in determining the convection pattern observed at high latitudes.

Consider the case for Bz southward first. The solar wind travels with velocity V_{SW}. In the case of the opened field lines, if B_{SW} is the magnetic field of the solar wind, then an electric field exists which in a reference frame fixed at the Earth is:

$$\mathbf{E}_{sw} = -\mathbf{V}_{sw} \times \mathbf{B}_{sw} \qquad (1)$$

In the direction parallel to the Earth's magnetic field B, charged particles move freely. Hence, the Earth's magnetic field lines usually act like a perfect electrical conductor, transmitting perpendicular electric fields and voltages across vast distances with no change in the potential in the direction parallel to B. Thus, the electric potential established due to the IMF will apply across the magnetosphere and thus map down to ionospheric heights in the polar cap. This electric field will thus drive plasma in the F-region in the anti-sunward direction with a velocity given as:

$$\mathbf{V}_I = \frac{\mathbf{E}_I \, X \, \mathbf{B}_I}{B^2_I} \qquad (2)$$

Because the magnetic flux density is higher in the ionosphere than in the solar wind, and since the equipotential surfaces converge, the electric field in the ionosphere is larger than in the solar wind. The plasma in the polar ionosphere will therefore move in an anti-sunward direction (Figure 3) due to the mapping of the induced electric field produced from the merging of the solar wind magnetic field to the Earth's magnetic field.

Consider the electric field generation in the closed field line region of the magnetosphere. Due to the interaction of the solar wind, the Earth's magnetic field lines are distorted. The resulting magnetic geometry has a

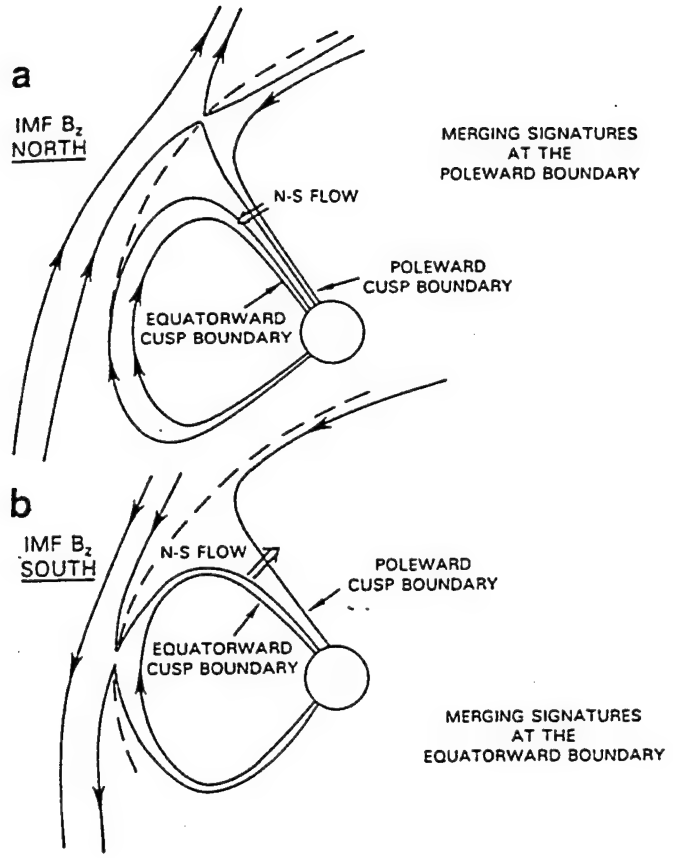
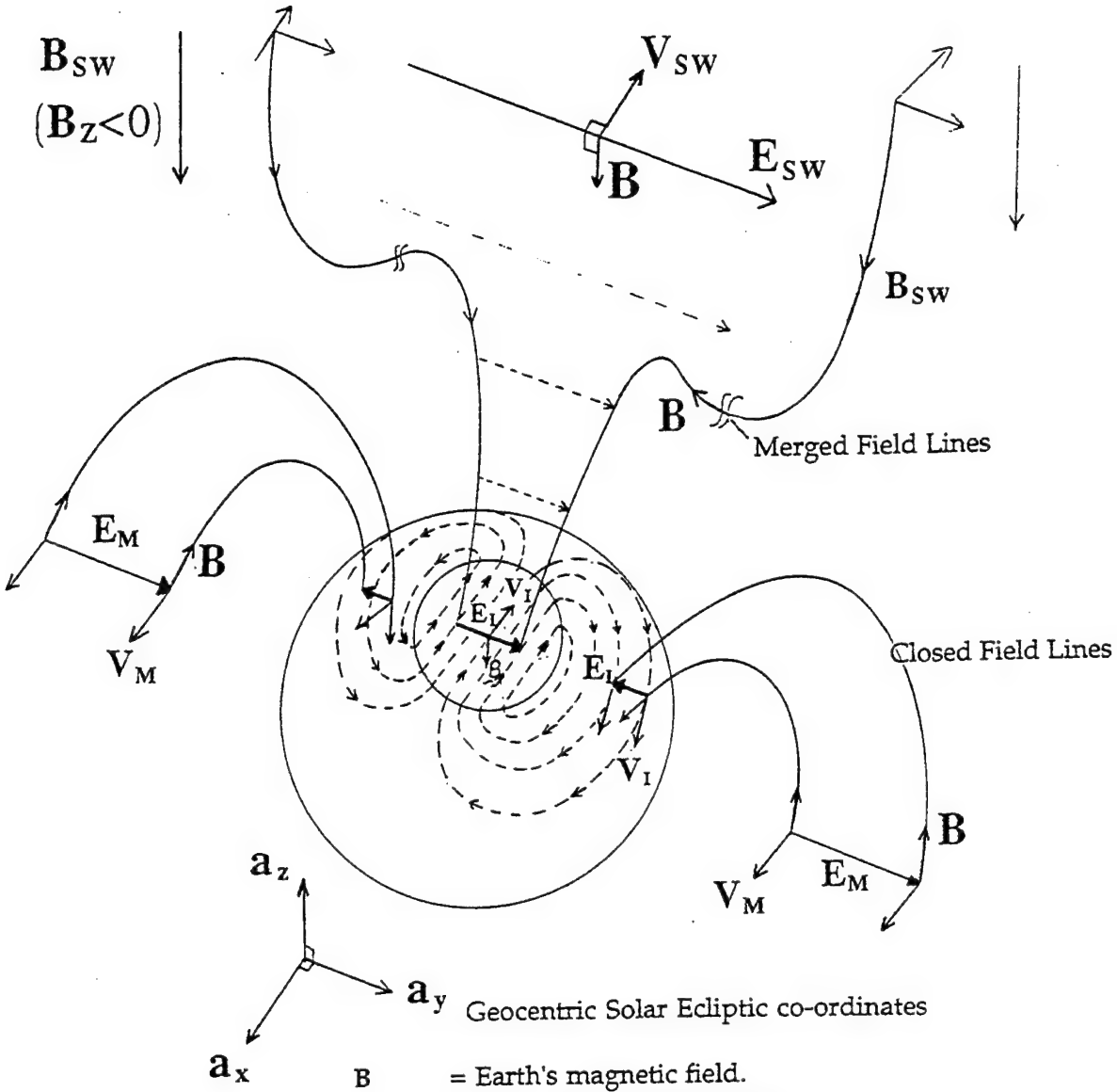


Figure 2. Diagrams of the merging of the IMF and Earth's magnetic fields on the dayside, taken from Basinska 1992. a) When Bz>0 the merging occurs at the poleward boundary [Russell 1992]. b) When Bz<0 merging occurs when the field lines are anti-parallel, at high latitudes on the dayside [Crooker 1986].



B	= Earth's magnetic field.
B_{SW}	= Solar wind magnetic field
E_I	= Electric field mapped to altitudes in the ionosphere.
E_M	= Electric field induced in earth's closed field lines.
E_{SW}	= Electric field induced from mergeing of B_{SW} and B.
V_{SW}	= Velocity of Solar wind plasma.
V_M	= Velocity of plasma in earth's closed field lines.
V_I	= Velocity of plasma in the earth's ionosphere

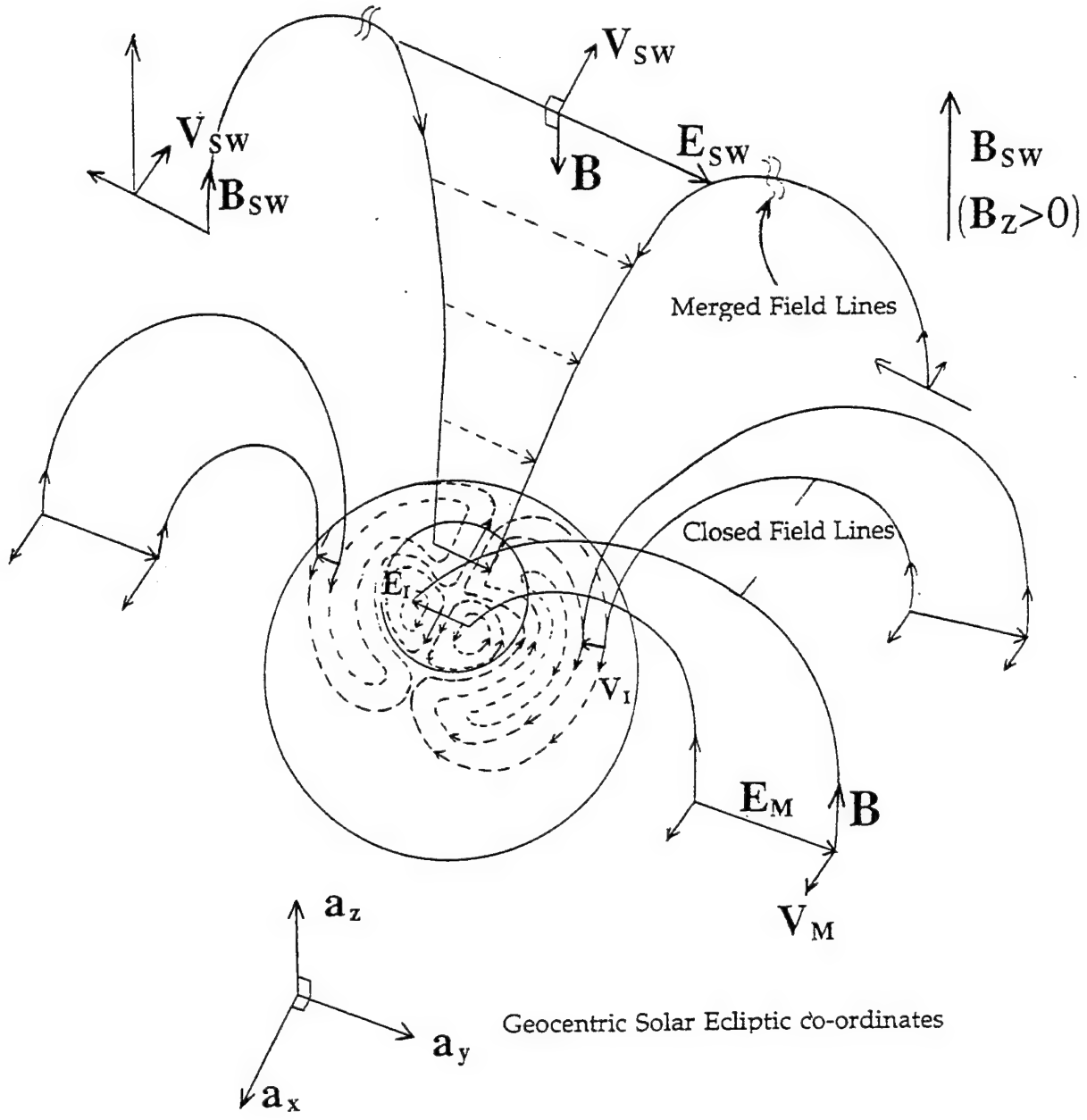
Figure 3. Idealized two cell convection pattern set up when IMF Bz <0.

tension that exerts a force on the plasma. This together with the pressure gradient and the potential difference applied across the magnetosphere by the flowing solar wind, produce motion of the magnetospheric plasma on the closed field lines toward the sun. This motion induces a dawn to dusk electric field in the tail. Since this electric field is attributed to the flowing properties of the solar wind rather than its electro-magnetic properties, its dawn-to-dusk orientation will not be effected by the orientation of the Bz component.

In Figure 3, the electric field established in the magnetosphere due to the V_m motion of the plasma towards the sun is mapped to ionospheric heights. In the closed field environment, this electric field drives the plasma in the ionosphere sunwards establishing the outline of a two-cell motion. A great deal of literature exists discussing the two-cell motion described, so we will not devote any in-depth discussion of its characteristics at this stage but continue to the case when the IMF Bz component is pointed northward (Bz>0).

In the case of the IMF Bz component being positive, a complete understanding of convection pattern and dynamics involved is still being developed. However, to a first approximation, we may use the discussions above to outline what convection pattern is possible. In the case of the open field lines, a Bz northward IMF component will induce a dusk-to-dawn electric field. When the IMF field lines merge with the Earth's magnetic field however, the induced electric field points from the dawn-to-dusk (Figure 4), as previously, and the plasma flows in an anti-sunward direction. Yet, as shown in Figure 2, the field lines merge poleward of the dayside cusp. This results in the field lines in the dayside polar region being closed.

For the case of the closed field lines as previously discussed, the magnetospheric electric field remains unchanged pointing from the dawn-to-dusk. Mapping of this electric field to lower latitudes drives the plasma sunward. Similarly, this field is also mapped to the dayside polar region and the addition of this sunward flow causes two smaller cells to develop. The two larger, lower latitude cells which would normally be observed for



B_I/B_{SW} = 50,000 nT/5 nT $= 10^4$

E_I/E_{SW} = 5 mVm^{-1}/1mVm^{-1} = 50

V_I/V_{SW} = 1 kms^{-1}/400 kms^{-1} = $2.5x10^{-3}$

Figure 4. Idealized four cell convection pattern set up when IMF Bz >0.

Bz<0 and the two new smaller cells rotate in opposite directions. This "four" cell system has been observed experimentally; however, its characteristics are not as yet fully understood.

While the Bz component controls the location of the merging field lines and so determines the coarse structure of the convection pattern (two cell or four cell), the By component controls which field lines must contribute to the polar convection pattern. Hence, variations in By are outlined by the distortion of the two or four cell system. Figure 5 displays the orientation of modeled two cell convection patterns calculated by Heppner and Maynard [1987] for different By conditions. Also included are the Digisonde velocity measurements made at Qaanaaq, Greenland. This figure indicates that when By<0 the dawn cell expands and the velocities in the polar region have directions slightly east of anti-sunward. When By>0 the dusk cell dominates and velocities are directed west of anti-sunward direction. Both these features are clearly observable from the drift measurements made at Qaanaaq. Figure 6 displays the orientation of a four-cell system for different By values. (Taken from Kelley, 1989, p284). When By is small, the two smaller cells are symmetrical about the noon-midnight meridian. For By<0 the dusk cell tends to expand into the dawn side and when By>0 the reverse situation occurs.

3. DIGISONDE STATISTICAL DATA BASE

In order to determine Bz and By orientations it was necessary to interpret the velocities measured at a polar latitude station with known IMF orientations. An example of the Digisonde velocity data was already given in Figure 5. From data obtained from Qaanaaq over a three year period (1989-1991) estimates of the behavior of the motion of plasma due to different IMF conditions was possible. An example of how systematic the velocity pattern can be for certain IMF orientations is given in Figure 7 (Crowley et al., 1992). Figure 7 displays the polar plot for the average velocity behavior for Bz>0 (top left plot). The velocity behavior measured on day 253 1990 is given on the right top plot along with the IMF Bx, By,

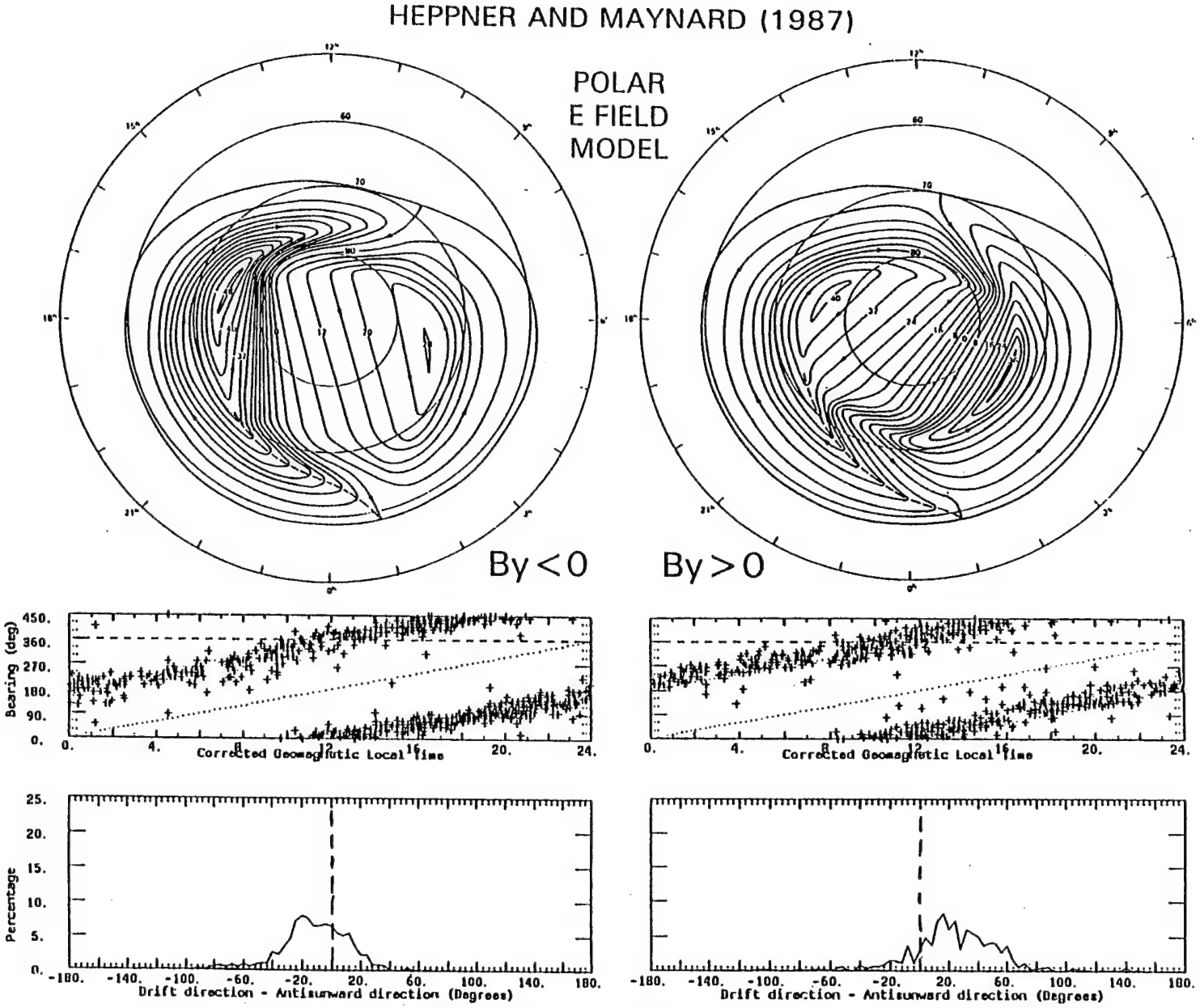
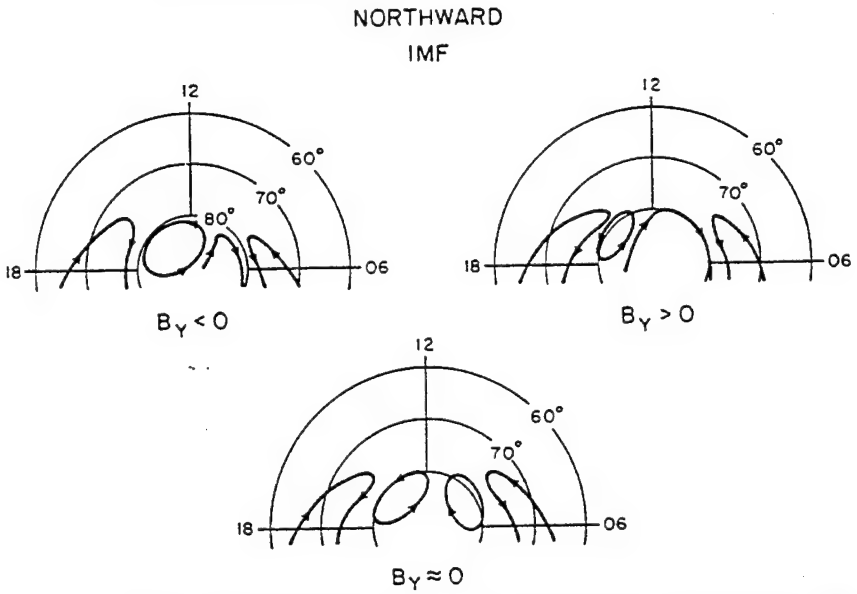


Figure 5. Polar E-field model results taken from Heppner Maynard [1987] showing the orientation of a two cell system for different By signs. Also displays Digisonde drift results obtained from data recorded at Qaanaaq (Greenland) in 1989.



The main feature of the dayside convection geometry when the IMF has a northward component is the existence of four convection cells. However, the dependence of the convection pattern on B_y leads to the dominance of one of the high-latitude cells and a three-celled pattern arises. [After Heelis *et al.* (1986). Reproduced with permission of the American Geophysical Union.]

Figure 6. Displays the orientation of a four cell system for different By values, taken from Kelly [1989] page 284.

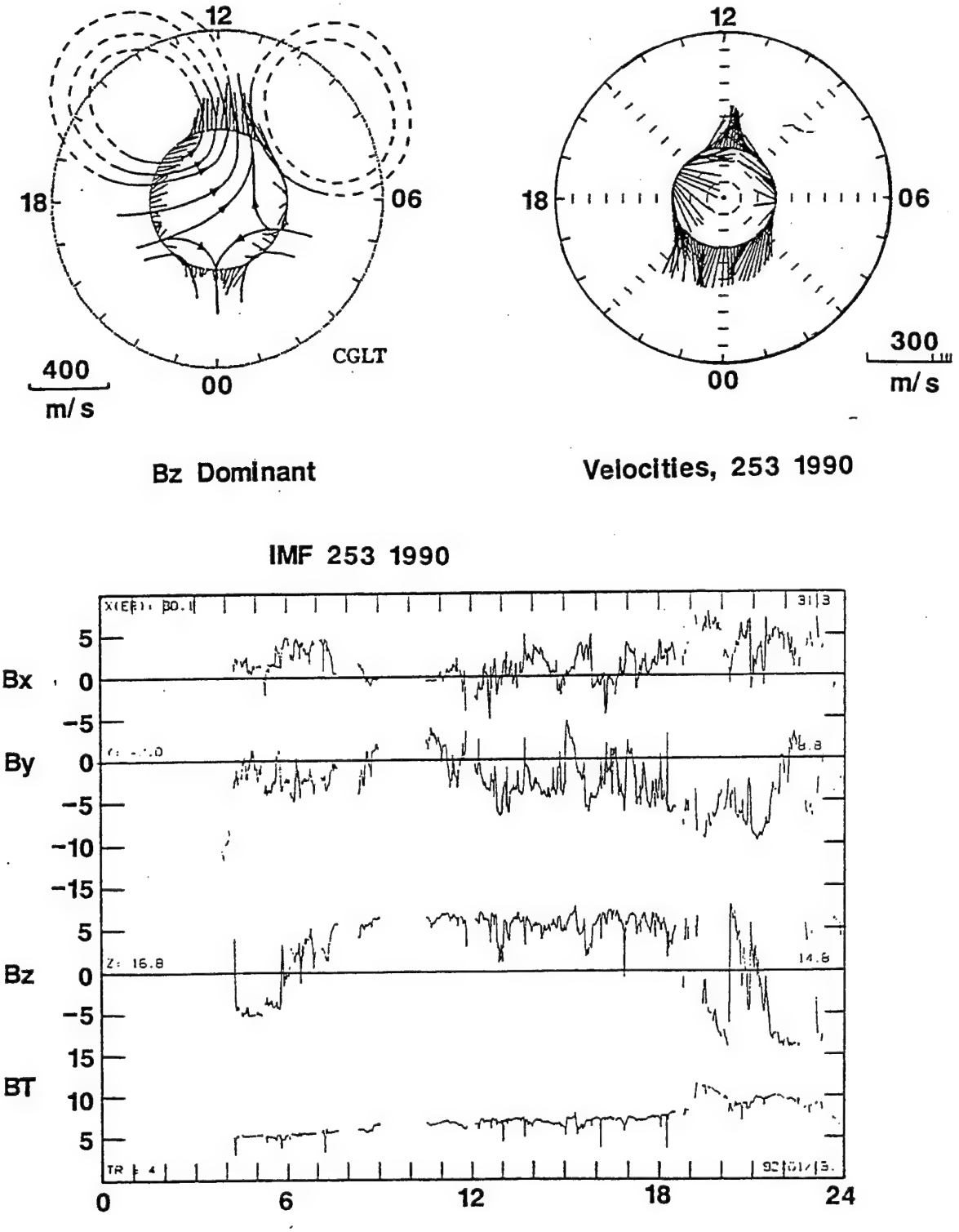


Figure 7. Top left displays averaged horizontal drift velocity component behavior for Bz>0. Top right displays the horizontal drift velocity component measured on 10 Sept. 1990, Bottom graph displays the IMF results for 10 Sept. 1990.

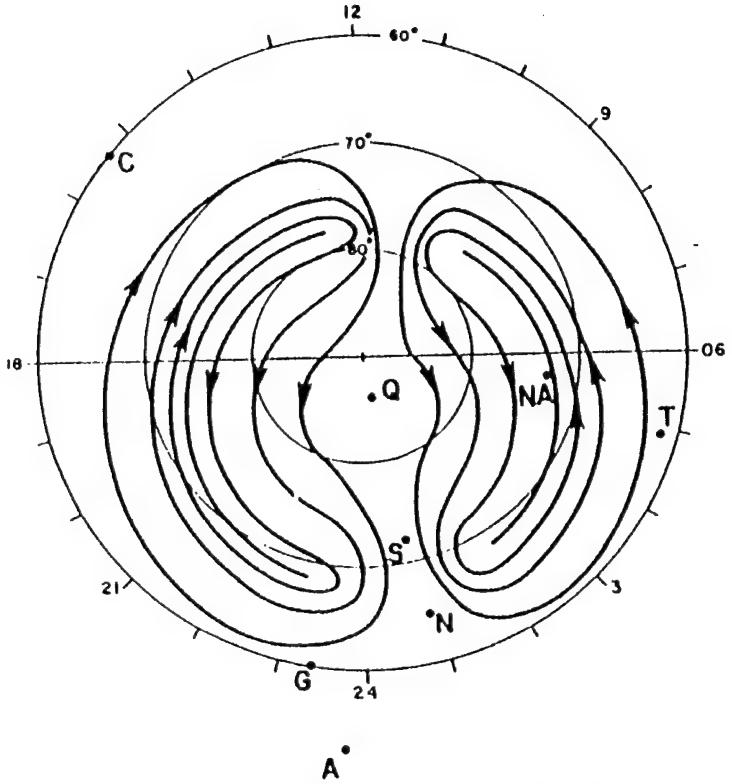
and Bz components measured for this day (bottom plot). Clearly, on day 253 1990 Bz>0 and By<0 for most of the day.

The velocities measured on this day show a similar pattern that is expected from the statistically averaged data. Hence, the top left plot is a good representation of velocity (convection) to expect when Bz>0 and By<0. Indeed one can characterize further comparisons such as these quickly and indicate what the Bz and By orientations are by just observing the drift velocities. Considering a simple two-cell convection pattern it is possible to outline the velocity behavior that should be observed at a number of latitudes. Figure 8 shows a simple two-cell pattern and the direction of the measured drift velocity that should be expected at four high-latitude stations.

The velocity plots are given as drift angle plotted as a function of time. For Bz<0 at Qaanaaq the velocity component should be consistently anti-sunward. This is reflected in the linear graph for Qaanaaq as a gradual progression of the velocity direction from north through south to north in a 24-hour period. The signatures for the velocity directions expected at other stations reflect the stations location with respect to the convection cells.

Figure 9 shows drift data measured at Qaanaaq on days 99 to 101 1991. The horizontal velocity magnitude, vertical velocity and the azimuthal direction of the horizontal velocity are given in this plot. On day 99 the plasma flow is strictly anti-sunward. On day 100 after 12UT sunward motion is observed. We assume that at this time the Bz component reversed from southward to northward. Also, what is apparent is the lower horizontal velocity magnitudes when Bz>0. These two distinct and simple characteristics of the behavior of the convection during changes in the IMF clearly indicate that the drift velocities may be used in the determination of the orientation of the IMF components.

Comparing known IMF orientations and velocity measurements made over one year, criteria were developed that relate variations in velocity to the signs of Bz and By. Figure 10 displays a year of Qaanaaq drift data plotted



POLAR DIGISONDE NETWORK AND THE CONVECTION PATTERN

	°CG LATITUDE
QAANAAQ	87
NY ALESUND	75.5
SONDRE STROMFJORD	75
NARSSARSSUAQ	69
TROMSO	66
COLLEGE	65
GOOSE BAY	65
ARGENTIA	58

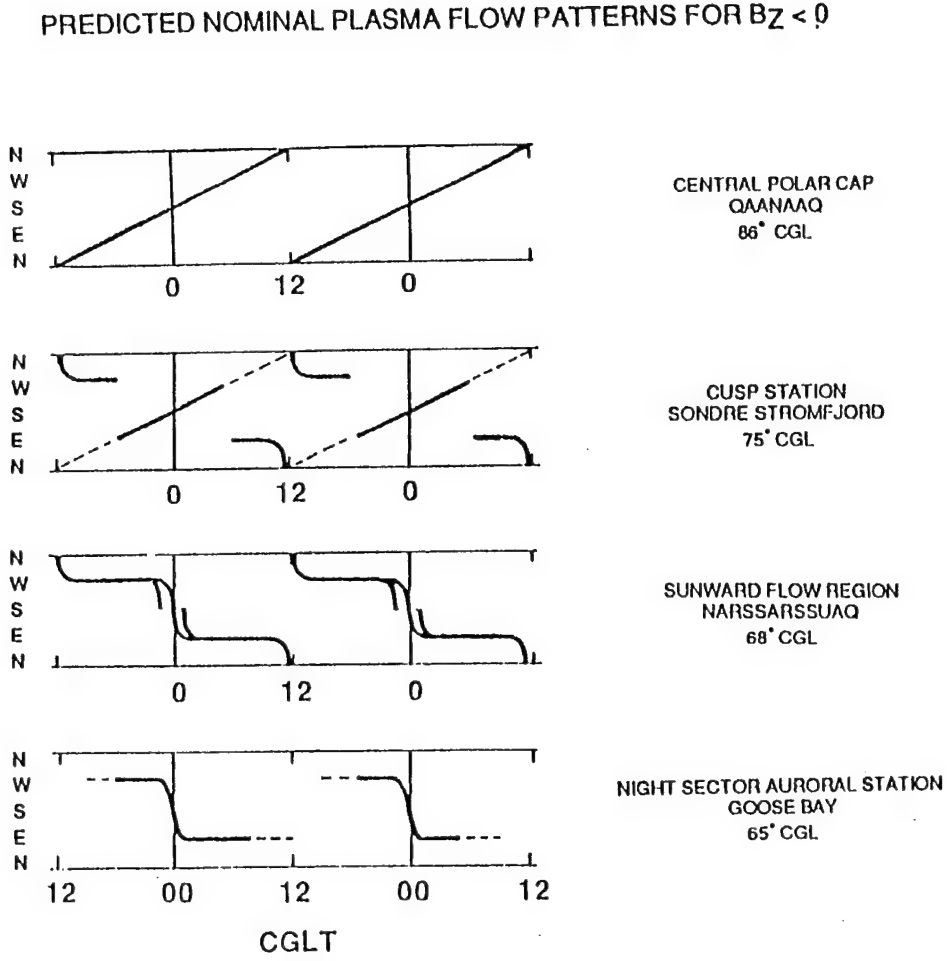


Figure 8. Shows the predicted Azimuthal directions for the horizontal velocity components that should be observed at four high latitude stations when considering a simple two cell convection pattern.

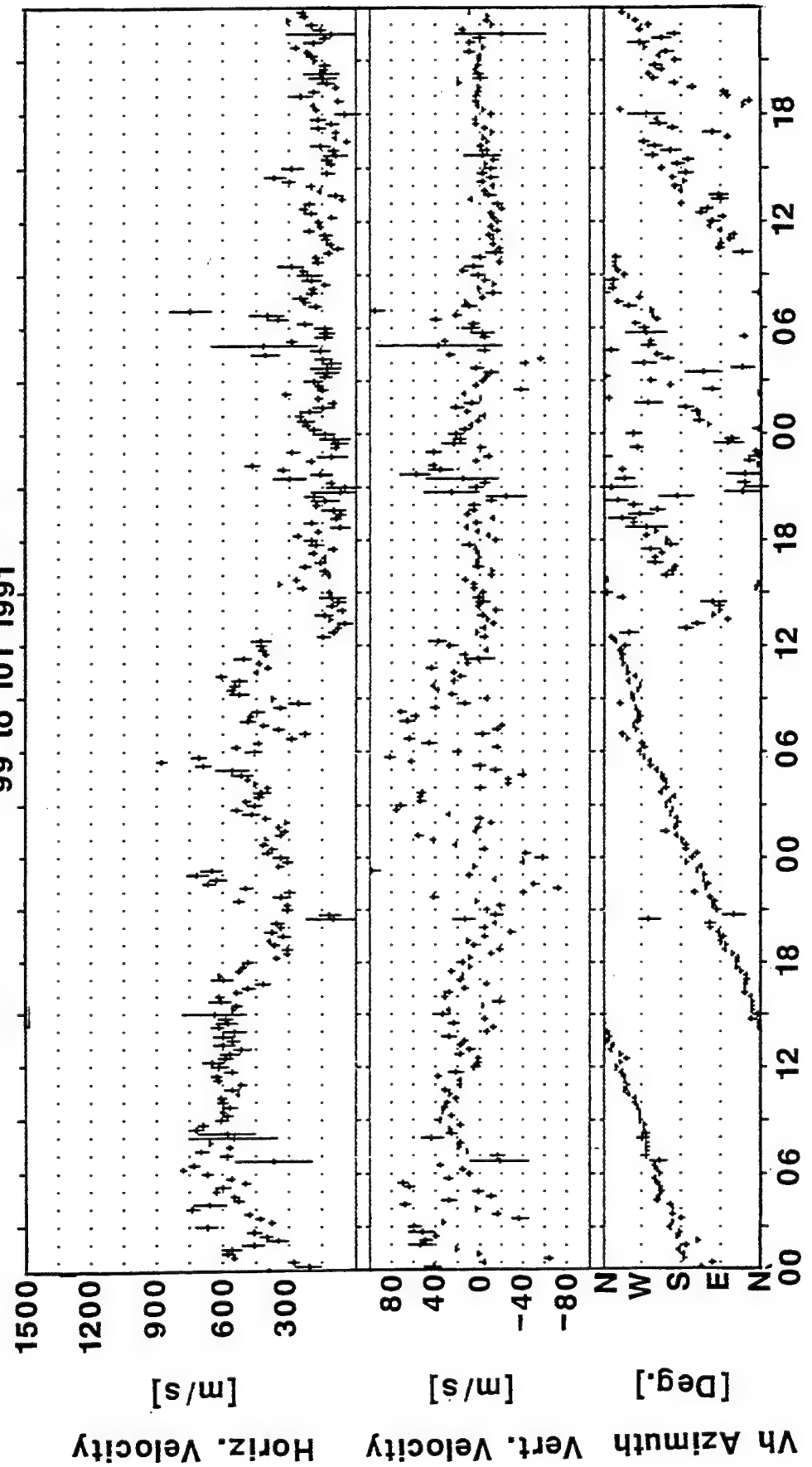


Figure 9. Shows Drift data measured at Qaanaaq (Greenland) from 9 to 11 April 1991.

for different Bz conditions. What is clear from this figure is the existence of a sunward drift observed during 08 to 18CGLT for Bz>0 which is nonexistent for Bz<0. From the discussions in Section 1 this is not surprising. The sunward flow of plasma around 12CGLT for Bz>0 correlates well with the development of the four cell system. In this Figure alone, a criteria exists that if sunward motion is observed between 08 and 18CGLT, Bz is definitely positive.

The extent and intensity of the spread observed in the scatter plots shown in Figure 10, indicates that distribution limits could be imposed on this data in order to test if a velocity component belongs to Bz<0 or Bz>0 condition. Figure 11 shows a set of horizontal drift velocity distributions produced for 3 hour periods. The movement of the mean of these distributions from -180 to 180 degrees outlines the anti-sunward motion observed in Figure 10. Each distribution has a finite width represented by a standard deviation of 20 degrees. Testing a horizontal velocity azimuth against any one of these distributions would indicate if the velocity measured is anti-sunward or sunward. Developing such tests would, in turn, allow us to interpret the orientation of the IMF components. For example, 12CGLT at Qaanaaq a horizontal velocity azimuth of 160 degrees was measured. From the statistical distribution given for 1030 to 1330CGLT the anti-sunward motion has a mean at 10 degree and a standard deviation of 20 degrees. The measured velocity must clearly be classified as sunward, not anti-sunward and with reference to Figure 10 one can immediately conclude that the Bz component is positive.

In developing a statistical testing package, a list of criteria for different IMF Bz and By orientations was established which is summarized in Table 1. One important feature is that the larger velocities are always associated with Bz<0, and that for Bz>0 no substantial separation in the velocities is noticeable.

4. RESULTS FOR THE DETERMINATION OF BZ AND BY COMPONENTS

Using the criteria above and allocating confidence weights for the one, two

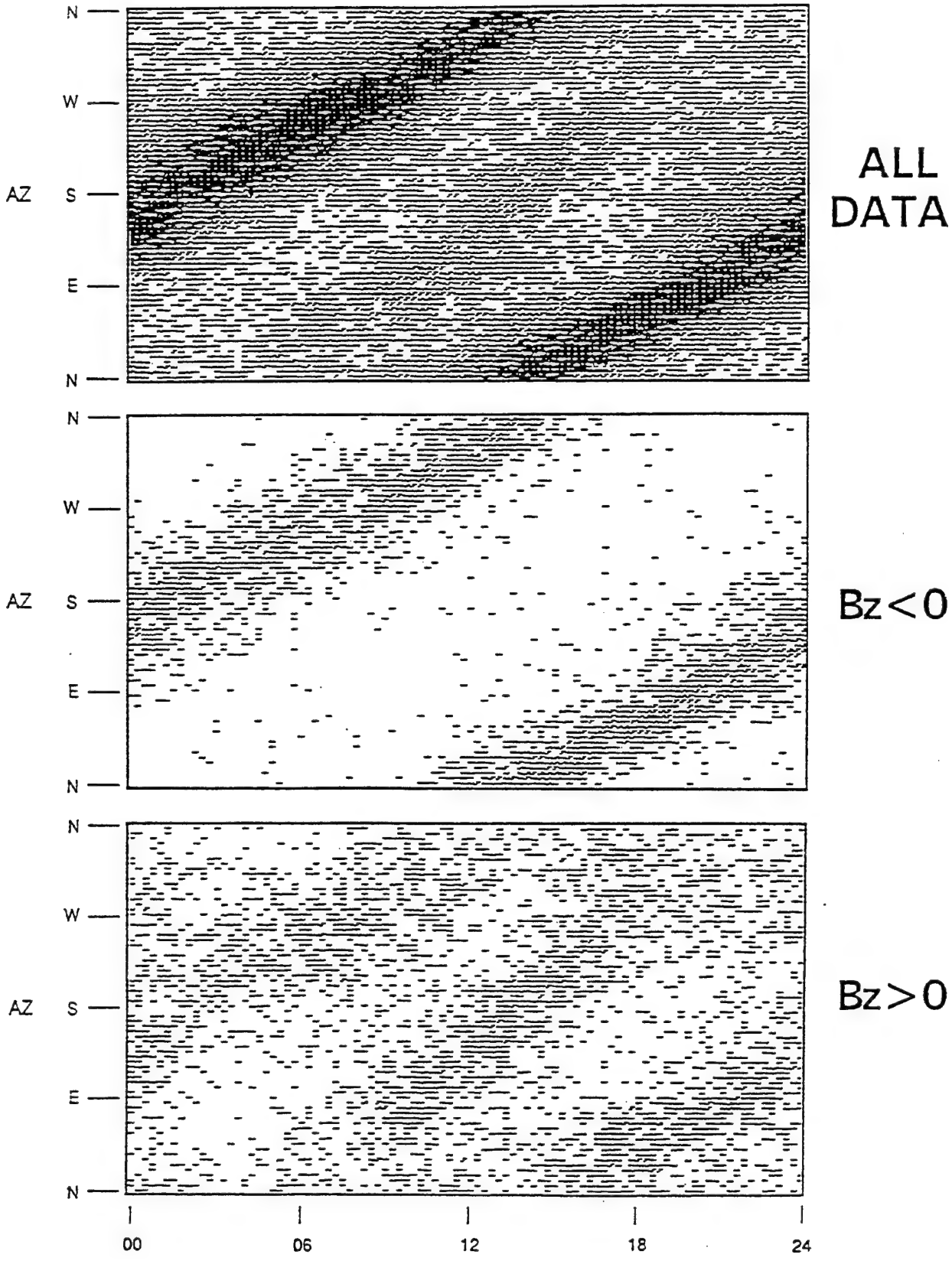


Figure 10 Displays a year of Qaanaaq drift data plotted for different Bz conditions. Only the azimuthal direction of the horizontal velocity component is plotted.

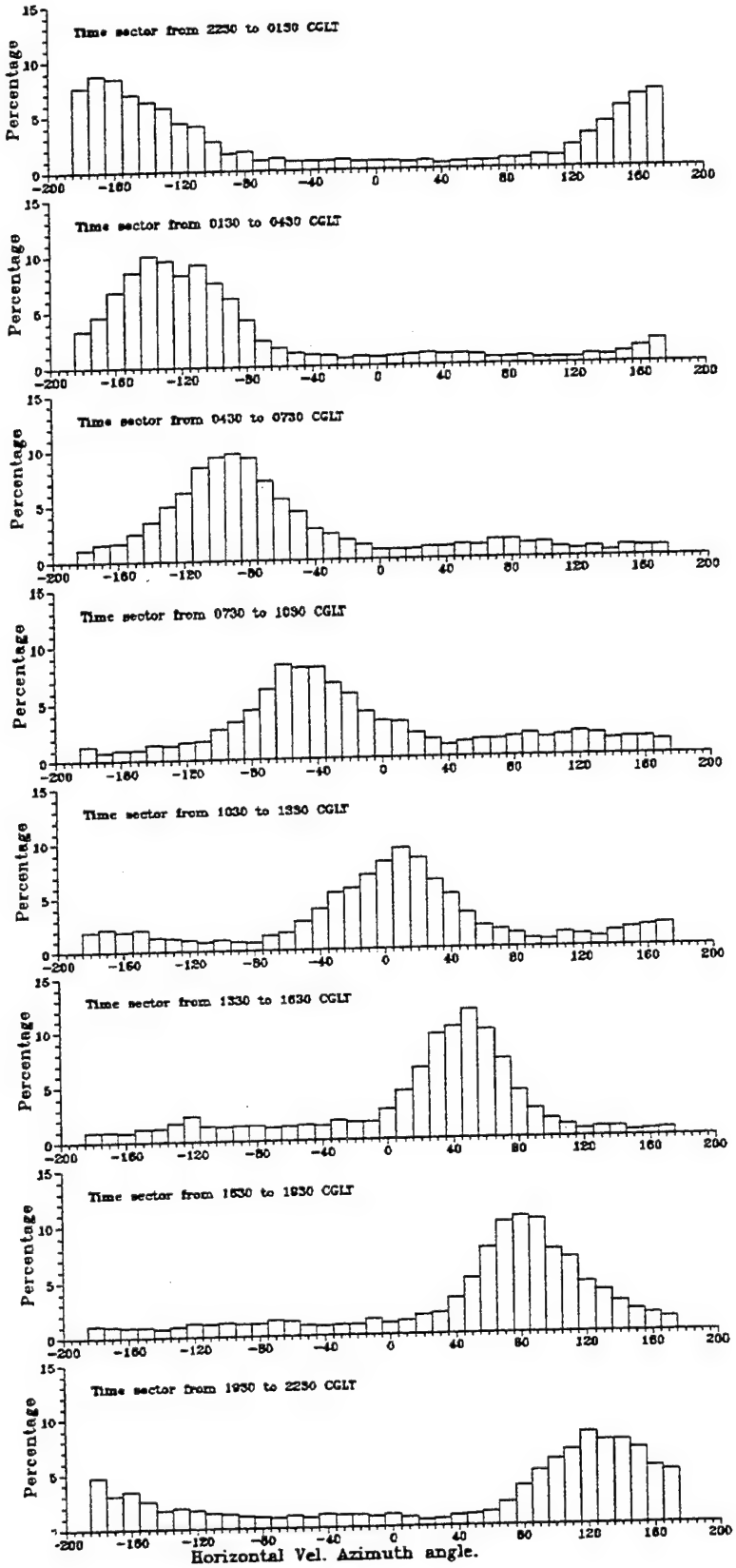


Figure 11 Probability histograms for the direction of drift motion at Qaanaaq. 1989 data was used with velocities calculated from sources which had less than 10 degree phase error. All data independent of IMF. Azimuth angle is measured from north.

Table 1. Drift Criteria for Different IMF Bz and By Orientations

IMF	Deviation (degree) Drift-Anti-sunward		Horizontal Magnitude m/s		Time Int. (CGLT)
	Mean	S.D.	Mean	S.D.	
Bz ≤ 0	0	20	>=600	100	ALL
By ≤ 0	<0	60	<=200	100	01 to 12
By ≤ 0	<0	60	>=600	100	13 to 24
By > 0	>0	60	>=600	100	01 to 12
By > 0	>0	60	<=200	100	13 to 24
Bz > 0	180	20	<300	100	
By ≤ 0	<0	60	<=200	100	18 to 06
By ≤ 0	>-180	60	<=200	100	07 to 17
By > 0	>0	60	<=200	100	18 to 06
By > 0	<180	60	<=200	100	07 to 17

and three standard deviation it is possible to determine the sign of the IMF Bz and By components from the Digisonde velocity measurements. Dependent on which increment the velocity value was located would indicate how confident the determined Bz and By orientation was. Figure 12 displays a comparison of determined Bz and By orientations and actual measured IMF values recorded for 1 January 1989. The continuous line displays the satellite measured IMF value while the dashed line gives the sign of the IMF value determined from the Digisonde velocities. The overall comparison is good; the percentages of times Bz and By were determined correctly were 95.4 and 81.6 respectively. In this example, some inconsistencies in the determination of the sign of the IMF By component can be seen.

Testing this method with one year worth of drift data recorded at Qaanaaq, it is possible to determine the correct IMF Bz and By orientations 60-70% of the time. Figure 13 shows the percentage distributions for the determination of Bz and By from the 1989 drift data collected at Qaanaaq.

Keeping in mind that all CGL times are tested, and only a single velocity measurement is used at any one time to determine the Bz and By components, this result is surprisingly good.

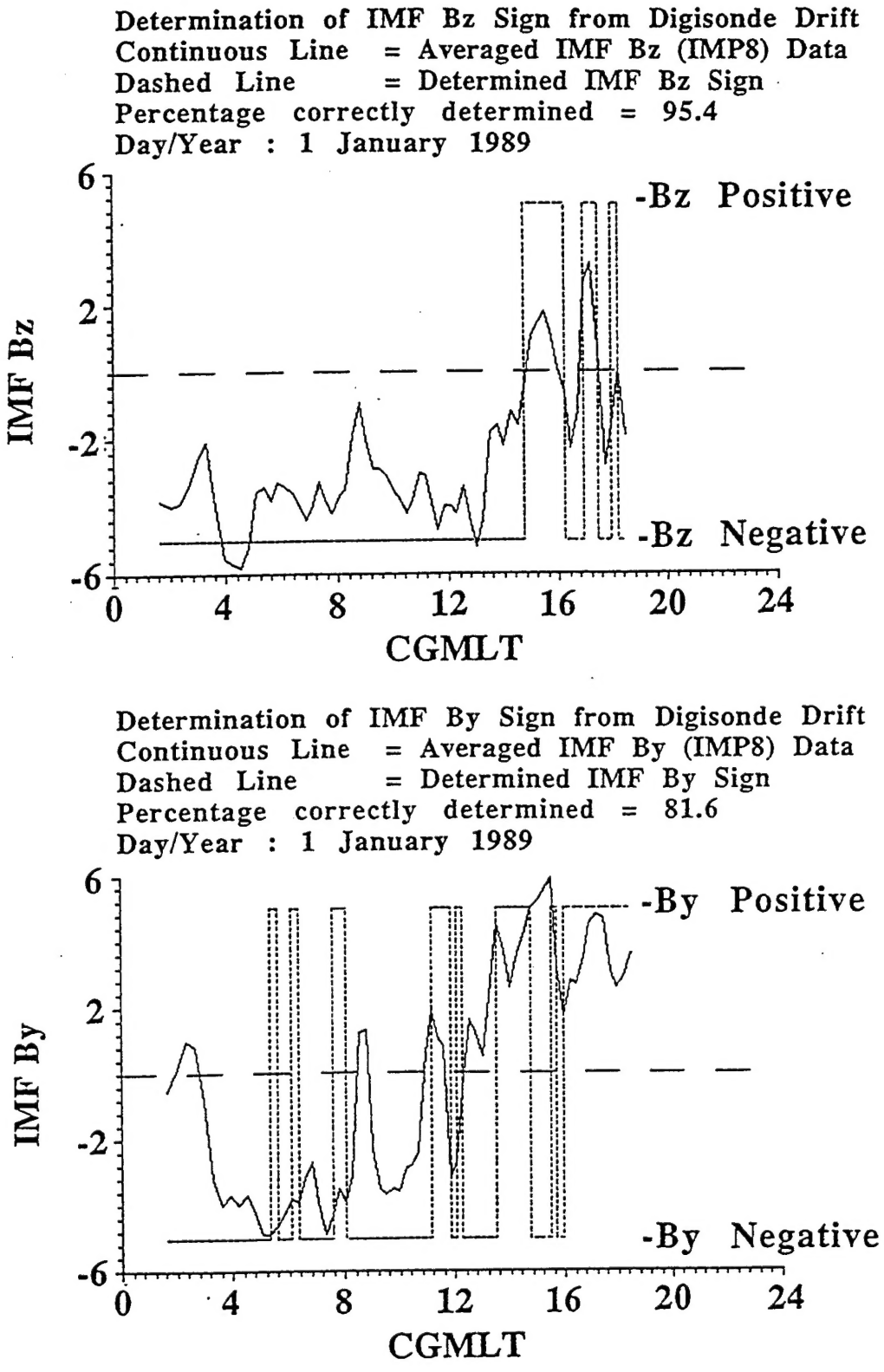
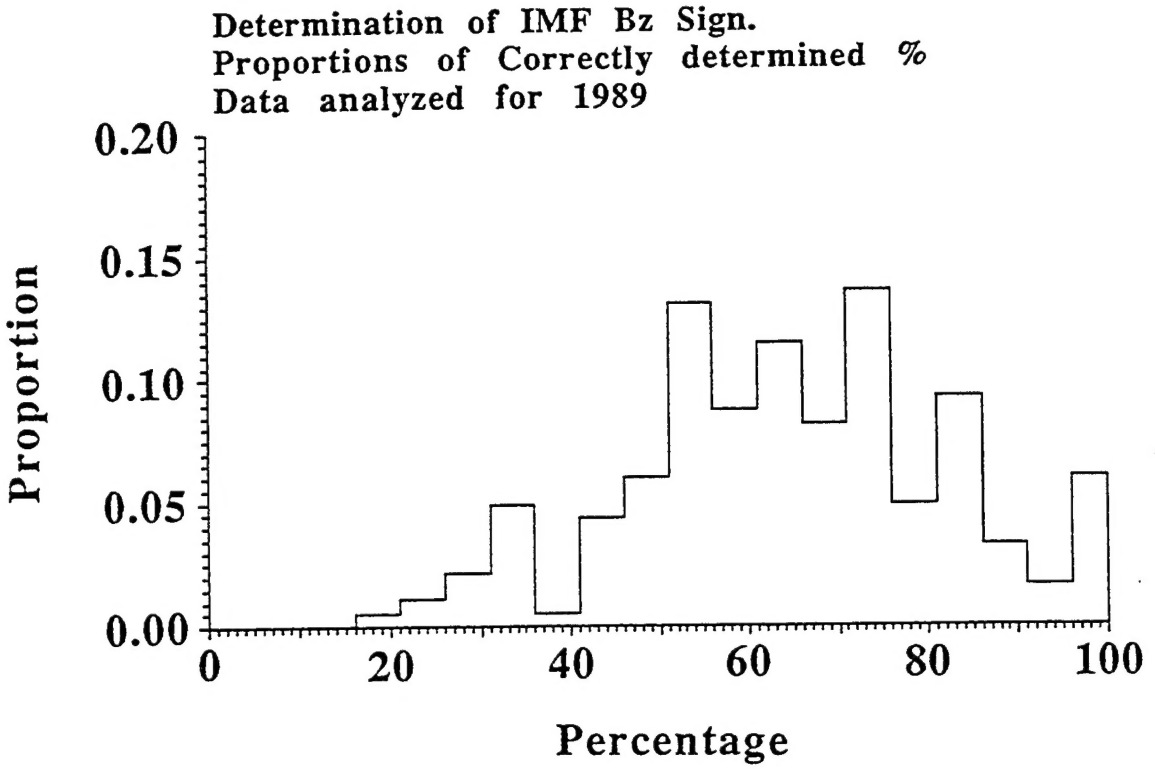


Figure 12. Comparison of the determined sign of the IMF Bz and By components using Digisonde velocity data, and IMF data recorded from the IMP-8 Satellite (Courtesy of R. Lepping GSFC).



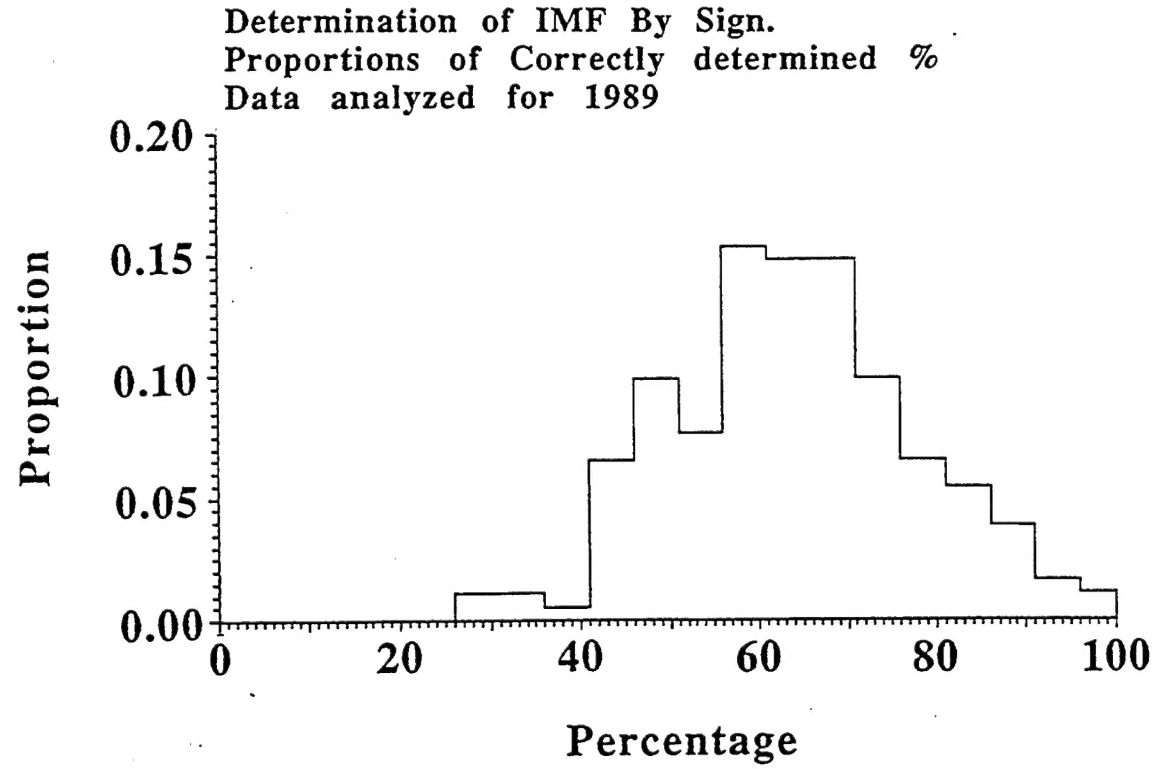


Figure 13. Proportion of the percentage of correctly determined IMF Bz and By signs for 1989 data analyzed.

The method which bases its results on a single station and only one velocity measurement, still requires additional work in order to improve on the determination of IMF Bz and By components. The areas that still need to be addressed are:

1. Introduce a time history into the analysis to indicate if an individual determined IMF orientation is consistent with previous measurements, or if the IMF Bz and By signs have changed.

2. Due to overlapping of similar velocities for certain time periods these methods should only be tested when the stations are in those CGLT sectors where the convection patterns are clearly defined for different Bz and By orientations. As an example, at Qaanaaq Bz may be unambiguously determined during the time interval from 09 to 15 CGLT when Bz<0 produces anti-sunward flow and while Bz>0 produces sunward flow. However, from 09 to 15 CGLT anti-sunward convection is observed for both Bz>0 and Bz<0. Hence, for Qaanaaq it would be best to rely only on the determined values when the station is located in the 09 to 15 CGLT sector (see item 4 below).

3. Improve the velocity calculation in the presence of velocity shears in the field-of-view of the sounder.

4. Use other high latitude stations to cover all time periods and several latitudes to establish a more robust prediction capability for the Bz and By directions.

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